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SUMMARY

Combustion tests of stoichiometric oxygen-hydrogen-helium mixtures and oxygen-hydrogen mixtures were made in a small chamber of 1-1/2 inches inside diameter and 15-1/4 inches inside length. The parameters varied were mixing procedure and mixing time, method of ignition, flame-path length, mixture composition, and initial loading pressure. Tests were also made in a large chamber of 6-1/4 inches inside diameter and 40 feet long, but most of the general conclusions reached are based on tests in the small chamber.

Adequate mixing of the gases was found to be important in determining whether or not the burning was smooth. The order and rate of introducing the gases affected the mixing and hence the burning.

Of the four types of ignitors tried in the small chamber, three were found to be satisfactory. Some of these ignitors promoted detonation when the electrical energy for ignition was increased.

Detonation was found to be affected by the flame-path length in both the oxygen-hydrogen-helium mixtures and the oxygen-hydrogen mixtures.

When the helium content was varied from 70 to 88 percent, with stoichiometric proportions of oxygen and hydrogen and with the flame-path length held constant, a critical range was found between approximately 75- and 82-percent helium for which detonation occurred in the small chamber at relatively low initial pressures, but not at richer or leaner mixtures.

Increasing the initial pressure, with all other variables held constant, increased the tendency for detonation to occur within the critical range of approximately 75- and 82-percent helium.

INTRODUCTION

A new test facility being developed at Ames Research Center, the prototype of a hypervelocity free-flight facility, employs a combustion chamber 40 feet by 6-1/4 inches as a shock-tube driver. This chamber is designed for combustion of gaseous mixtures of hydrogen and oxygen in helium to produce high-temperature helium at pressures up to 50,000 psi. The problem is principally obtaining detonation-free combustion consistently since, even at moderate pressures, detonation could cause considerable damage to equipment and, possibly, injury to personnel. The associated properties of combustion, peak burning pressure and burning time, are of practical interest since they are measures of the performance and consistency of the combustion process. Although combustion and detonation have been studied (see refs. 1 through 12, among others), little information is available concerning the burning behavior of combustible gases at elevated initial pressures. In fact, from the information available, it seems that it may be difficult, even at moderate initial pressures, to obtain detonation-free combustion.

To investigate conditions for detonation-free combustion as well as to gain experience in working with combustible gases, preliminary tests were made in an available small combustion chamber prior to completion of the large chamber. The variables considered were: (1) mixing procedure, (2) mixture proportion, (3) ignitor and the associated ignition energy, (4) flame-path length, and (5) initial pressure. For most of the tests these variables were applied to helium-diluted mixtures. However, a few tests were made in the small chamber in which hydrogen was used as the diluent in place of helium.

Information obtained from the tests conducted in the small chamber was used to guide tests made in the large chamber upon its completion. The description of the large chamber as well as the experience obtained therefrom is presented in a separate section entitled Large Chamber Tests.

SMALL CHAMBER TESTS

Tests and Equipment

The parameters considered in these tests were investigated in the small combustion chamber shown in figure 1. This chamber was a steel tube of 1-1/2 inches inside diameter and 15-1/4 inches inside length. Pressures were measured by two piston-type strain gages mounted in each end plug as shown in figure 1. Reference 13 describes these gages. It was not possible with the existing end plugs to mount the gages so that the piston fits flush with the interior surface of the plug. Consequently, each gage had a 1-3/4-inch long cavity between the piston end and the interior surface of the plug. The cavity at the ignition end had a 1/4-inch diameter, the other a 1/2-inch diameter. Outputs from the two strain gages were amplified, displayed on oscilloscopes, and photographically recorded.

Mixing procedures.- Gases were introduced through a single port at the ignition end of the chamber (see fig. 1). Three loading procedures were used:

(1) for most of the tests, hydrogen and helium were allowed to mix in a high-pressure cylinder and, after at least 1-1/2 hours, were added to the oxygen in the combustion chamber; (2) in a few tests the gases were introduced into the combustion chamber one at a time, first oxygen, then helium, and finally hydrogen; and (3) in a few the order of introduction (2) was reversed. The gases were introduced in predetermined proportions and the pressure was measured with bourdon tube test gages. When helium was the diluent, the hydrogen and oxygen proportions were stoichiometric (i.e., one part oxygen to two parts of hydrogen by volume). Mixtures ranged from 70-percent helium (1:2:7)[1] to 88-percent helium (1:2:22). Gases were at room temperature when added. Time was allowed for temperatures to regain equilibrium following the introduction of each gas. Initial loading pressures were varied from 300 to 8,000 psi.

Ignition systems.- Basically, four types of ignition sources were tried: (1) an exploding wire, (2) a heated wire, (3) a Pyrofuse wire which when heated burns and emits burning particles, and (4) a spark gap. These four types with variations are presented in the following tabulation with the corresponding energy components.

Type of ignitor	Energy components
1. Exploding manganin wire, 0.0015-inch diameter	
a. Single 1/2-inch length at end of chamber	7.5 μf, 1/2 to 9.3 kv
b. Multiple 1/2-inch lengths connected in series and spaced axially along length	7.5 μf, 2 to 4 kv
c. 13-inch length mounted axially	7.5 μf, 5 to 10 kv
2. 13-inch length heated tungsten wire, 0.005-inch diameter	7.5 μf, 3 kv
3. Chemically reacting wire (Pyrofuse)	
a. Single 1/4-inch length at end of chamber	90-volt battery
b. 13-inch length mounted axially	7.5 μf, 3 kv
4. Spark gap, steel electrodes, 0.005- to 0.020-inch spacing	12-volt battery and ignition coil

No change in performance was observed when, in a few tests, the manganin wire diameter was changed to 0.003-inch nor when the capacitance was changed to 15 μf. (When the 15 μf capacitance was used, the voltage was adjusted to keep the ignition energy equal to the ignition energy for the 7.5 μf capacitance.) Except for the batteries, the ignition energy is discharged rapidly (in about 20 microseconds) through the ignitor.

Flame-path length variation.- The flame-path length was varied in one of three ways: (1) by using a single "point source" ignitor at the ignition end and by placing steel plugs at one end to shorten the flame-path length from approximately 13-3/4 inches to 1-1/2 inches in steps of 1-3/4 inches, (2) by using the 1/2-inch wires connected in series and spaced at varying intervals, as desired,

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[1]Ratio of oxygen, hydrogen, and helium by parts of volume.

or (3) by using a long continuous wire on axis inside the tube to make the path length equal to the tube radius to obtain the minimum flame-path length of 3/4 inches.

Hydrogen as a diluent replacing helium.- A total of 27 tests were made in which hydrogen replaced helium as the diluent. The mixtures ranged from 78- to 90-percent hydrogen. (It should be noted that the fuel[2] content in these mixtures varied from 66 to 30 percent, whereas in the helium-diluted mixtures it varied only from 30 to 12 percent.) The initial pressures were varied from 500 to 1,250 psi. The ignition systems used were either the single 1/2-inch-long manganin wire exploded (usually at voltages of 1/2 to 1 kv although voltages as high as 4 kv were tried) using a capacitance of 7.5 μf or a single 1/4-inch length of the chemically reacting wire heated with two 45-volt batteries connected in series. The order of loading the gases was oxygen first, then hydrogen.

Results and Discussion

All of the variables considered had some effect on obtaining consistent detonation-free combustion and on the associated pressure ratios and burning times. Table I contains a summary of the tests made. In addition to test conditions, this table includes the type of burning obtained for most of the test conditions and indicates on which figure, if any, the data may appear. The only tests not included in the table are those made with the spark gap ignitor, and the reason for this omission is given in the section on ignition.

The data recorded were photographic oscilloscope records of the pressure and time histories of each test and visual observations of the equipment following the tests. Also obtained but not included herein were recordings of the sound of the burning which did not vary significantly with different types of burning.

Classification of burning.- Three classifications were used to identify different types of burning: (1) smooth burning or combustion, (2) rough burning or onset of detonation, and (3) detonation. Figure 2 shows pressure records representative of the three types of burning that occurred in the small chamber. The smooth curve in figure 2(a) is for the adiabatic combustion process, with a decay after the peak corresponding to cooling of the burned gas; figure 2(b) is interpreted as rough burning or onset of detonation indicated by the discontinuity in the pressure-time curve; and figures 2(c) and 2(d) are interpreted as detonation. It should be noted that in figure 2(c) only the qualitative appearance of the trace suggests that detonation occurred since the peak pressure "spike" is relatively low. The reason that shock reflections are not visible in figure 2(c) as they are in figure 2(d) is possibly the difference in sweeping speeds used. The sweeping speed used to obtain figure 2(d) was 5 milliseconds per centimeter whereas for figure 2(c) it was 100 milliseconds per centimeter, so that any reflections would be compressed and thus not distinguishable. Consideration of the slow sweep speed used for figure 2(c) and the present brightness intensity of

[2]The word "fuel" as used in this report denotes the reactant gases, namely, the stoichiometric proportion of hydrogen and oxygen contained in the mixture.

the trace can explain why the entire pressure spike is not visible. However, for these tests, results similar to those exhibited in the last three figures represent conditions to be avoided.

Effects of varying the method of ignition.- The method of ignition and the energy involved will be discussed first since, after a satisfactory ignitor was found, it was not varied.

The exploding manganin wire was found to be satisfactory when a single 1/2-inch length or a multiple number (2 to 8) of 1/2-inch-long wires were connected in series with a voltage ranging from approximately 500 to 3,000 volts. For one test, when the voltage for a single 1/2-inch wire was increased to 9.3 kv, the burning was identified as combustion but the burning time was unduly long and pressures were low compared to results of other tests with otherwise comparable conditions. Some detonations occurred with the single 1/2-inch wire and were attributed to the flame-path length; this will be discussed later. When the length of the exploding wire was increased to 13 inches and mounted axially in the chamber, the burning performance was not satisfactory. It was not possible to explode this length at 2 kv, so 5, 7.5, and 10 kv were tried. Combustion occurred when 5 and 7.5 kv were used but the burning time, as with the single 1/2-inch wire with 9.3 kv, was unduly long and the pressures were low. Detonation occurred each of three times when 10 kv were used. Figure 2(c) is a record from one of these tests. It is likely that a long exploding wire would be more satisfactory in a larger diameter chamber. For example, reference 2 reports the satisfactory use of six wires 23 feet long exploded simultaneously in a 27-inch-diameter bore. However, since the single 1/2-inch wire or the multiple 1/2-inch wires were reliable at voltages ranging from 500 to 3,000 volts, efforts were not made to make the long length exploding wire workable. The ignitor used for most of the tests was the 1/2-inch wire (single or multiple) but other means of ignition were tried.

The performance of a 13-inch-long tungsten wire of 0.005-inch diameter was satisfactory when heated with 3,000 volts at 7.5 μf. This voltage, as determined from open-air bench tests, caused the wire to glow brightly along its entire length and yet not explode or break. The current discharge through the ignition wire was very rapid, occurring in approximately 20 microseconds. This time is sufficiently short to prevent preheating of the gases or any appreciable sagging of the wire prior to ignition of the gases. This ignitor was used only three times but it produced time and pressure records comparable to those obtained with the multiple exploding wires and was considered to be an adequate ignition system.

Satisfactory results were also obtained with a 13-inch-long chemically reacting wire when heated with 3,000 volts at 7.5 μf or a single 1/4-inch length heated with two 45-volt batteries connected in series. As will be discussed in a later section, the former of these ignitors produced faster burning times than others, and it was possible to ignite some mixtures at a lower initial pressure than was possible with some of the other ignitors.

Considerable ignition difficulty was encountered with a single spark gap and, when ignition was achieved, it occurred at different times on repeated tests. Much of this difficulty is believed due to inadequate control of the variables, such as electrode geometry, gap spacing, ignition energy, etc., and therefore these tests are not included in table I. Reference 3 contains a considerable amount of information on the use of spark gap ignition at low pressures and references 1 and 4 describe the satisfactory use of multiple-spark sources to ignite mixtures up to loading pressures of 500 psi. At initial pressures up to 2,500 psi in the present tests, ignition occurred occasionally but with an unpredictable delay time after the electrical energy was applied. It was therefore feared that multiple-spark gaps at high initial pressures might offer considerable difficulty in obtaining simultaneous ignition.

Effects of helium percentage and pressure level.- Since neither of these two variables can be discussed without referring to the other and since much of the data is plotted showing both the helium content and the initial pressure, both will be discussed together. In general, the helium percentage appears to be a more critical variable than the initial pressure level.

It had been expected that increasing the fuel content and/or initial pressure would tend to promote detonation, as indicated in references 1, 4, 5, and 6, among others. However, a surprising result of the tests, shown in figure 3, indicates that detonation may be promoted in some cases by increasing and in other cases by decreasing the fuel content. This figure shows that for a flame-path length of 13-3/4 inches, detonation or onset thereof occurred with mixtures between approximately 75- and 82-percent helium whereas combustion occurred with richer as well as leaner mixtures at the same and considerably higher loading pressures. The dashed line indicates a possible boundary of a critical region where small variations in the helium content influence the type of burning. Tests made to substantiate the data show good repeatability. Test conditions outside the critical region resulted in good burning and those inside resulted in detonation or onset of detonation (except for one test at 77.2-percent helium and 1,500 psia pressure). No effect of increasing the initial pressure was observed outside the critical region. Tests were not made at pressures higher than those shown in the critical region because it was assumed that a further increase would not suppress detonation. The effect of initial pressure level on detonation pressures is shown in figure 4. These pressure-time histories are of four tests using a 78-percent helium mixture. Note the similarity of the pressure traces, except for the pressure peaks, at different initial pressure levels. As previously discussed the spike tip is not quantitatively indicative of the actual peak pressures. The original photographs are not shown because scale factors varied in each case making visual comparison quite difficult.

The effect of helium content on burning times for initial pressures from 1,000 to 8,000 psi and one ignition method is shown in figure 5. The burning rate, for tests resulting in adiabatic combustion, increases rapidly with decreasing helium content. The times for initial pressures less than 1,000 psi were not included in this figure because they appeared to depend upon initial pressure. Above 1,000 psi, initial pressure showed little or no effect on burning time as illustrated by the two data points at 1.04 seconds from tests in which the initial pressures were 4,000 and 8,000 psi and as shown in reference 7 for tests between 1,000 and 2,000 psi. Figure 5 of reference 4 shows that increasing the initial pressures from 200 to 500 psi increased the burning time for 70- and 80-percent helium mixtures. (Burning times for the few tests made at pressures less than 1,000 psi are presented in a later figure.)

The effect of helium content on ratios of peak pressure to initial pressure is shown in figure 6 for two flame-path lengths and for initial pressures of 1,000 psi and above. (The flame-path-length effect will be discussed in a later section.) The scatter shown is due possibly to incomplete burning in some cases but is not believed due significantly to varying the initial pressure, as illusted, for example, by the data points at 82-percent helium with a flame-path length of 13-3/4 inches; most of these data were obtained at the same initial pressure of 3,000 psi. Decreasing the amount of helium caused an increase of the peak pressure as expected. The theoretical ratio of peak pressure to initial pressure was computed from perfect gas relationships as found in most thermodynamic textbooks (see, e.g., ref. 14). This theoretical ratio is included in the figure for comparison purposes. The pressures from which the experimental pressure ratios were computed were obtained from the strain gage located in the end plug with the 1/4-inch-diameter cavity (see fig. 1). These pressures were consistently higher than those measured in the end plug with the 1/2-inch-diameter cavity by approximately 7 percent regardless of the test conditions. A number of strain gages were used so it is felt that the difference was not due to individual gages. Filling the cavities with an inert substance, such as stopcock grease, did not affect the difference. Although the reason for this observed difference in pressure is not known, the higher value at the ignition end was used simply because pressure measurements were not always taken at the other end.

Variations of the helium content, the initial pressure, and the ignitor had an effect involving the flammability of a gas mixture. (Ref. 3, p. 761, shows the effect of initial pressure variation on flammability limits for mixtures of natural gas and air.) Flammability limits, as such, were not investigated in the present tests but some results on flammability in helium-diluted mixtures were found which may be of interest to some readers. For example, 85-percent helium mixtures could not be ignited with the 1/2-inch exploding wire at 3,000 psi but were ignitible at 4,000 psi and above; whereas the same mixture was ignitible at an initial pressure of 2,000 psi with the Pyrofuse wire. Table I lists these and other tests where ignition did not occur. (The nonignition results for helium and initial pressures of 300 to 500 psia are not due to flammability limits but to other effects which will be discussed later.)

Effects of varying the flame-path length.- Varying the flame-path length generally affected detonation tendencies, burning times, and peak pressures. These will be discussed in the order named above.

The effect of the flame-path length on detonation tendencies is shown by the comparison of figures 3 and 7. The first figure shows that in the critical region already discussed, a 13-3/4-inch flame-path length caused detonation or its onset at pressures of 1,000 psi or above. However, when the flame-path length was reduced to 12 inches or less, combustion occurred in this region as shown in figure 7.

The effect of varying the flame-path length on burning times for 77- and 82-percent helium mixtures is shown in figure 8. As can be seen from this figure, the burning time varies systematically with flame-path length for each mixture. (The manner in which the flame-path length was varied did not affect the results.) The scatter of the 82-percent data is probably caused by slight deviations in the helium percentage affecting the time of burning much more in the leaner fuel mixtures than in the richer fuel mixtures. This effect is shown in figure 5 by the steep slope of the curve at the leaner fuel mixtures.

As was previously mentioned, the chemically reacting wire (Pyrofuse) produced much shorter burning times than did the heated tungsten wire. This difference is believed due to an effect of flame-path length. Although both wires were of the same length and are mounted in a similar manner, the Pyrofuse wire emits sparks radially which may very well shorten the actual flame-path length, and thus the burning time.

As can be seen in figure 6, at the same helium percentages, the longer flame-path length caused lower peak burning pressures. This is believed due to the longer time available for heat losses to the chamber wall for the slower burning mixtures.

Effects of mixing procedure.- When premixed helium and hydrogen were added to oxygen in the combustion chamber, burning was smooth. However, results from some tests made at low initial pressure show that when the gases were introduced into the combustion chamber one at a time, the order of introduction appeared to be important. These results are shown in figure 9. When oxygen was introduced first, then helium, and then hydrogen, ignition did not occur with helium mixtures from 74 to 79 percent. The 73-percent mixture burned but burning times were unduly long and burning pressures were low even when the flame-path length was reduced by means of multiple exploding wires. Five tests with a 70-percent helium mixture resulted in detonation each time. When the order of introduction was changed so that the hydrogen was introduced first, followed by helium, and last by oxygen, the results were comparable to those obtained with the original order of mixing - adding premixed helium and hydrogen to the oxygen. Figure 10 shows a difference in the burning time for the three mixing orders. Although no attempt was made to find a reason for this difference, it is interesting to note that mixing order does affect burning time. (For the two mixing orders in which the gases were introduced one at a time, the flow rate was approximately the same.)

Effects of using hydrogen as a diluent in place of helium.- The tests involving hydrogen as a diluent are included in table I. The flame-path length and mixture proportions were both found to affect the burning of these mixtures as had been the case for the helium-diluted mixtures. However, mixture proportions had a greater effect than did the flame-path length. For example, with a loading pressure of 500 psi and a flame-path length of 13-3/4 inches, combustion was obtained with an 87.5-percent hydrogen mixture (62.5-percent diluent mixture shown in table I). At the same loading pressure, however, the use of hydrogen mixtures of 81 percent or less caused detonation or its onset even for a flame-path length as short as 1-1/2 inches. The records of figure 5, reference 9, show combustion of a 90-percent hydrogen mixture at an initial loading pressure of 4,000 psi and possibly the onset of detonation (characterized by disturbances travelling the length of the tube, both during and after combustion) of an 85-percent mixture at an initial loading pressure of 1,000 psi. The closed combustion chamber of reference 9 had a 4-inch diameter and a 43-inch length and used a single-point exploding wire as the ignition source located at one end of the chamber.

The ratio of peak pressure after combustion to initial loading pressure was found to increase with decreasing hydrogen content, and this ratio was also apparently affected by the flame-path length and the initial loading pressure which was varied from 500 to 1,250 psi. The pressure ratio increased with increasing initial pressure and decreasing flame-path length.

The effect on combustion of increasing the voltage applied to a 1/2-inch exploding wire is shown in figure 11. These pressure traces were obtained from tests in which the voltage was varied between 1/2 and 4 kv and in which a 90-percent hydrogen mixture, a loading pressure of 750 psi, and a flame-path length of 13-3/4 inches were used. The second trace appearing on each of the three photographs is a reference trace to depict the initial pressure level. (In the last photograph, however, the oscilloscope setting had shifted between the time the reference trace had been photographed and the time ignition occurred.) Figure 11(a) shows combustion at 1/2 kv, figure 11(b) onset of detonation at 2 kv, and figure 11(c) detonation at 4 kv. Evidently, increasing the ignition energy was sufficient to cause detonation under conditions where smooth burning could also be observed. It should be noted, however, that the pressure records do not show excessive pressures for either of the last two figures.

LARGE CHAMBER TESTS

Tests and Equipment

The tests described in this section were made in the 6-1/4-inch-diameter by 40-foot-long combustion chamber mentioned in the Introduction. This chamber is the shock-tube driver for a blowdown-type wind tunnel. The objective of these tests was to obtain consistent performance of the combustion driver and not, as it had been for the small chamber, to investigate the effects of individual variables on combustion.

The combustion chamber is shown schematically in figure 12. Pressure-time history measurements were made, using two piston-type strain gages and one piezo-electric gage, at the locations shown in this figure. Gases were introduced by means of a manifold on the inside of the chamber extending the full length and containing holes of 0.020-inch diameter drilled at 1-foot spacings.

Because of the large size and high fineness ratio of this chamber (80 compared to 10 for the small chamber), it was anticipated that the results from the small chamber would not be directly applicable to a chamber this much larger. Although the experience gained from the small-chamber tests was used insofar as possible, certain changes became necessary either from the standpoint of obtaining better combustion results or of obtaining a more efficient operation of the aerodynamic facility of which the combustion chamber is a part. These changes were not always made singly or in a systematic manner. Therefore, it is not possible in some instances to draw conclusions as to particular merits of certain changes. Research testing in the facility test section has not as yet required the high initial loading pressures originally contemplated for this large chamber.

Combustion has been obtained consistently up to initial pressures of 815 psia with burning pressures up to 5,000 psia, but the combustion is not entirely satisfactory because of pressure oscillations that occur after peak burning pressure has been reached.

Results and Discussion

Types of burning.- Examples of several kinds of pressure traces from these tests are shown in figures 13(a) through (f). The first is representative of detonation, the second of onset of detonation, and the next four of combustion, with the last one showing the best smooth combustion performance. (The irregularities observed in fig. 13(f) on the trace following burning were due to some noise signals received on the oscilloscope and were observed visually prior to the test.) The ignition energy was supplied 11 milliseconds after the start of the trace except in the case of figure 13(f) where the trace started at the same time the energy was applied to the ignitor. The pressure oscillations shown in figures 13(c) and 13(d) proved to be the most persistent problem.[3] These oscillations are believed due to the burning rate not being uniform throughout the chamber and are believed to be generated by unequal pressure along the length of the combustion tube at a given instant of time. The result is that the gas moves from the high-pressure regions to the low-pressure regions and reflects from the tube ends causing the oscillations or "slosh waves." The shape of the pressure trace varies from the rather sinusoidal appearance shown in figure 13(c) to one in which the pressure waves sometimes appear to develop to shock strength shortly after completion of burning as shown in figure 13(d). It is believed that lack of adequate mixing is largely responsible for the slosh waves.

Other investigators have obtained oscillation-free combustion in oxygen-hydrogen-helium mixtures in chambers with both smaller and larger diameters but with smaller length-to-diameter ratios. Reference 1 shows pressure records with oscillations similar to some observed in this investigation as well as some without any detectable oscillations. Those without oscillations were obtained with fuel mixtures of 75- and 80-percent helium (stoichiometric proportions of oxygen and hydrogen) at initial pressures of 300 and 500 psia, respectively. These tests were obtained in a chamber with a fineness ratio of 40 and the investigators found that the amplitude of the oscillations increases as the fuel content is increased. Figure 5 of reference 2 shows a typical record of an oxygen-rich mixture (82.3 percent inert[4] mixture) ignited at an initial pressure of 750 psia which does not show oscillations during or after combustion. The combustion chamber of reference 2 is 24 feet long with a 27-inch-diameter bore (fineness ratio of 10.7).

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[3]The sudden drop in pressure occurring in figures 13(c) and 13(f) is due to the shock-tube diaphragm rupturing. These records were obtained in air-flow runs of the facility.

[4]The word "inert" in this report denotes those gases which do not react chemically during the burning process. It is assumed that the hydrogen and oxygen in stoichiometric proportions do react chemically.

The variable most affecting the combustion performance in the large chamber is believed to be mixing, although the ignition system and mixture proportions have had some effect. These three variables will be discussed separately.

Mixing methods.- Three different methods have been used in trying to obtain uniform gas mixtures in the combustion chamber: (1) introducing each gas separately, (2) introducing the three gases simultaneously, and (3) putting the gases into a common pressure vessel equipped with a fan and allowing the gases to "mix" before dumping them into the combustion chamber.

The first method with several variations has been used for the most part. Initially, the loading manifold was located above the tube axis and the gases were added without regard to the flow rate of the gas being loaded. With the manifold in this location, the best order of introducing the gases appeared to be hydrogen, then helium, and oxygen last. However, out of 12 tests, 3 resulted in detonation, 5 resulted in the onset of detonation, and only 4 resulted in combustion. Allowing the gases to mix in the combustion chamber prior to ignition for times varying up to four hours did not improve the burning performance, indicating that time alone was not a satisfactory means of obtaining uniform mixing. When the manifold was lowered to its present position on the bottom of the chamber as shown in figure 12, the best order seemed to be oxygen first, then helium, and hydrogen followed by helium to clear the lines. However, consistent combustion was not achieved until the helium and the hydrogen were added at a high flow rate which apparently had a much greater influence on mixing than did time. The loading procedure adopted was similar to that reported in reference 4 in that the oxygen was added first, followed by about 50 percent of the helium, then the hydrogen, and last by the remainder of the helium. No detonation attributed to mixing has since occurred; however, the pressure oscillations that occur after combustion are considered objectionable. Combustion with almost no oscillation has recently been obtained by a variation in this loading procedure. The loading procedure was changed in that the amount of helium added to the oxygen before introduction of the hydrogen has been reduced considerably. The combustion pressure-time record shown in figure 13(f) was obtained from a 1:3:8 mixture in which only 14 percent of the total helium was loaded prior to adding the hydrogen.

Another variation in loading procedure consists in loading by increments. The gases are loaded in the same sequence as before but the amounts are reduced so that the sequence is repeated several times. (The helium is proportioned so that it always separates the hydrogen and the oxygen in the loading sequence.) This variation has been as satisfactory as the single sequence loading procedure, in which 50 percent of the helium was added after the oxygen, but requires more time.

The second method used consists in introducing the three gases simultaneously and has been successful in obtaining combustion, but the pressure oscillations observed on the pressure history have varied considerably from test to test.

The third method - premixing the gases in a separate chamber by means of stirring action from a fan rotating at 1,200 rpm for as long as two hours - has been disappointing. No detonations have occurred from its use but pressure oscillations of rather large amplitude have still been present.

Ignition systems.- Three basic ignition systems have been tried in this chamber: multiple exploding manganin wires, aluminum foil notched to provide multiple ignition points, and a long heated tungsten wire.

Initially, the ignition system consisted of twenty-seven 1/2-inch long manganin wires, 0.0015-inch diameter, located on the center line, connected electrically in series, and spaced at approximately 18-inch intervals to provide a 9-inch flame-path length. On the basis of results of the small chamber tests, in which a 12-inch path length was sufficient to prevent detonation at initial loading pressures up to 7,500 psi, this path length was believed better than adequate to prevent detonation. The wires were exploded using a capacitance of 15 μf at 15 kv. This ignition system was used in only four tests and resulted in two detonations, one onset of detonation, and one combustion. This ignition system was abandoned and the framework necessary to hold the manganin wires was removed for the following reasons: (1) it might promote detonation by inducing turbulence (see refs. 8, 10, and 11); (2) its heat sink effect could result in lower final pressures; and (3) its preparation and installation for each test were laborious and time consuming. No conclusions can be drawn concerning the relative merits of the multiple exploding wires because of the methods used to load gases. For the three tests in which detonation or the onset of detonation occurred, the gases were introduced by a method later found to be poor; whereas for the test in which combustion occurred, the gases were loaded by increments.

The second ignition system tried used a strip of aluminum foil (0.0004 inch thick by 1 inch wide, mounted on cellophane tape for strength) which has proven satisfactory at the Naval Ordnance Laboratory (ref. 12). Notches in the foil at 18-inch intervals along the 40-foot length acted as high resistance ignition points. Two tests were made in the combustion chamber: In one ignition did not occur, and in the other onset of detonation occurred. The potential used was 6 kv at 15 μf. (The amount of energy required appeared to be critical since open-air bench tests showed that for both 0.0004- and 0.0011-inch foil, sometimes some but not all of the notches would vaporize.) In the case of the nonignition, it was believed that over the 40-foot span, the cellophane tape had stretched and the aluminum foil had separated, breaking the continuity. No further tests were made with this ignition system because it was feared that the 40-foot length of fragile tape was more than could be handled reliably.

The ignition system next tried, which is presently being used, consists of a 0.010-inch-diameter tungsten wire 40 feet long heated with a rapid discharge of 45 μf at 11 kv. (The amount of voltage used was selected, as with the small chamber tests, as that at which in open-air bench tests the wire glowed cherry red along its entire length without breaking.) The wire was stretched taut from the center of the breech plug to a bracket (see fig. 12) at the diaphragm end of the chamber. This bracket, at the diaphragm end, was originally mounted above the diaphragm piercing mechanism (located on the chamber axis) which caused the wire to be off axis by approximately 1 inch at this end. It was observed from the pressure records obtained at both ends of the chamber, that the diaphragm end always reached peak pressure later than the breech end. It was reasoned that the longer flame-path length, due to the off-center location of the wire at the diaphragm end, might result in the longer burning time obtained at that end. Accordingly, the wire was placed on the center line, behind the punch at the diaphragm end (see fig. 12), sacrificing some length, and the time to peak pressure at both ends did become almost identical. The magnitude of the pressure oscillations was reduced but not eliminated (see fig. 13(e)). The amount of sag along the 40-foot span is now approximately 3/16 inch, which still results in a slightly nonuniform path length to the wall.

Gas mixtures.- The first mixture tested consisted of 79-percent helium with oxygen and hydrogen in stoichiometric proportions (1:2:11.29). This particular mixture was chosen because some data were available from its use in a relatively large chamber (3-inch inside diameter by 9 feet in length). (See ref. 6.) Pressure records from five tests using this mixture showed that the burning results were not consistent and it was believed that uniform mixing was not being achieved. This belief was further strengthened in the next test in which an 85-percent inert mixture (1:3:16) was loaded into the combustion chamber at an initial pressure of 300 psia. Information obtained from the small chamber tests and from references 1 and 6 indicated a mixture of these proportions and at this pressure would not even ignite, but detonation did occur (see fig. 13(a)). This result therefore indicated quite clearly that instead of a uniform 85-percent mixture in the chamber, the helium content varied throughout the chamber and the gases must have been fuel rich enough to ignite in some locations but not in others, causing a long flame-path length which resulted in the detonation. Gas loading procedures and mixture proportions were then changed and consistent combustion has since been achieved except in four tests which will be discussed later. The chemical formulas for these mixtures are given in the following tabulation:

Combustible mixture		Percentage of diluent
$(O_2 + 2\ H_2) + H_2 + N_2 + 5\ He$		70
$(O_2 + 2\ H_2) + H_2 + KN_2 + (8 - K)He$,	$0 \leq K \leq 3.76$	75
$(O_2 + 2\ H_2) + 0.33\ O_2 + 8.67\ He$		75
$(O_2 + 2\ H_2) + O_2 + 8\ He$		75
$(O_2 + 2\ H_2) + 1.42\ O_2 + 7.58\ He$		75
$(O_2 + 2\ H_2) + 2\ O_2 + 7\ He$		75

Combustion was obtained using these mixture proportions; however, no conclusion can be made as to the relative merits of these mixtures since insufficient tests were made. When the combustion chamber is used to operate the shock tube, nitrogen is used as an additional diluent to adjust the temperature and speed of sound to desired values. The addition of nitrogen had no effect on the pressure oscillations.

In four tests using the 40-foot heated tungsten wire and a 75-percent inert gas mixture, detonation occurred because the tungsten wire was either fouled or broken. To prevent such detonations a modification has been made which permits the wire resistance to be measured before and after gas loading as well as immediately prior to ignition. Prior to this modification the resistance was measured before but not after gas loading.

SUMMARY OF RESULTS

Combustion tests of oxygen-hydrogen-helium mixtures were made in a small combustion chamber at loading pressures up to 8,000 pounds per square inch and in a large combustion chamber at loading pressures up to 815 pounds per square inch.

In the small chamber adequate mixing depended on the order in which the three gases were introduced. Pressure time-history records indicated that mixing of the gases was adequate for the following orders of introduction:

a. Hydrogen, helium, then oxygen.
b. Oxygen and then premixed hydrogen and helium.

In the large chamber the order of introducing gases and particularly the flow rate thereof was important in promoting mixing.

The ignition sources found to be the most satisfactory in the small combustion chamber were the 1/2-inch-long exploding wire, the chemically reacting wire, and the heated tungsten wire. In the large chamber, the heated tungsten wire was the most satisfactory ignition source tested.

For the small chamber a critical range of helium diluent precentages was found in which detonation would occur even at relatively low initial pressures. This critical range extended from about 75- to 82-percent helium for a flame-path length of 13-3/4 inches. When the helium content was reduced below about 75 percent or increased above about 82 percent, detonation did not occur. As the helium content was increased, the final pressure decreased and the combustion time increased.

Increasing the initial pressure in the small chamber tests increased detonation tendencies for certain mixture proportions. However, detonation could be suppressed at all initial pressures by reducing the flame-path length to 12 inches or less. Increasing the initial pressure beyond 1,000 pounds per square inch did not significantly affect the burning time.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., May 8, 1963

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TABLE I.- SMALL CHAMBER TEST CONDITIONS AND RESULTS

No. of tests	Flame-path length, in.	Percent diluent	Ignition voltage, kv	Initial pressure, psia	Results	Figure
DILUENT - HELIUM Mixing order: oxygen, premixed helium and hydrogen Ignitor - 1/2-inch single manganin wire						
5	13-3/4	87.9-88.0	2	1000 - 7000	No ignition	
1		85.1		3000	No ignition	
5		85.0-85.1		4000 - 8000	Combustion	3,5,6
4		82.4		675	No ignition	
8		82.0-82.1		3000 & 4000	Combustion	3,5,6,8
1		82.1	9.3	3000	Combustion	
3		81.9-82.1	2	4500	Detonation[1]	2(b),3
2		79.8-80.0		2000 & 2500	Combustion	3,5,6
4		80.0-80.1		3000	Detonation	3
4		78.9-79.0		1000 & 1500	Combustion	3,5,6
3		78.9-79.1		1500 & 2000	Detonation	3
5		78.1-78.2		1000 - 3000	Detonation[1]	3,4
6		77.1-77.2		1000 - 3000	Detonation[1]	3
1		77.2		1500	Combustion	3,5,6
1		76.4		675	Combustion	3,9,10
5		76.1-76.2		1000 - 3000	Detonation[1]	3
1		75.33		1000	Onset of det.	3
1		75.25		675	Combustion	3,9,10
20		74.5-75.2		1000 - 7500	Combustion	3,5,6
11		70.0-70.5		675 - 6000	Combustion	3,5,6,9,10
4	12	77.1-77.2		3000 - 7500	Combustion	7,8
2	12	76.0-76.1		4000 & 5000	Combustion	7
8	10-1/4	82.0-82.1		3000 - 8000	Combustion	2(a),7,8
3	10-1/4	79.0-79.1		3000 - 5000	Combustion	7
2	6-3/4	82.1		3000	Combustion	7,8
Ignitor - 1/2-inch multiple manganin wires						
9	3/4 - 6	82.1	1-4	3000 & 4500	Combustion	6,7,8
9	3/4 - 1	77.1-77.2	3	1500 - 7500	Combustion	6,7,8
1	3/4	85.1	3	3000	No ignition	
1	3/4	85.1	3	4000	Combustion	6,7
Ignitor - 13-inch manganin wire						
3	3/4	82.1	5 & 7-1/2	3000	Combustion	
3	3/4	82.1	10	3000	Detonation	2(c)

[1]Includes onset of detonation results.

TABLE I.- SMALL CHAMBER TEST CONDITIONS AND RESULTS - Continued

No. of tests	Flame-path length, in.	Percent diluent	Ignition voltage, kv	Initial pressure, psia	Results	Figure
DILUENT - HELIUM Mixing order: oxygen, premixed helium and hydrogen Ignitor - 13-inch tungsten wire						
3	3/4	77.2	3	2000 - 3000	Combustion	7,8
Ignitor - 13-inch chemical wire						
1 4 1 2	3/4 3/4 3/4 3/4	88.0 85.1 77.2 74.5-75.1	3 3 3 3	4000 2000 - 4000 2000 1000 & 3000	No ignition Combustion Combustion Combustion	 7 7 7
Mixing order: oxygen, helium, and hydrogen Ignitor - 1/2-inch single manganin wire						
6 2 1 4 5	13-3/4 13-3/4 13-3/4 13-3/4 13-3/4	79.0 76.0 75.0 73.0 70.0	0.55-1.1 0.55 0.55 0.55 0.20-0.55	300 & 500 300 & 500 500 300 & 500 300	No ignition No ignition No ignition Combustion Detonation	9 9 9 9,10 9
Ignitor - 1/2-inch multiple manganin wires						
3 2	3/4 3/4	78.8-79.6 73.0	3 3.9	300 & 400 300	No ignition Combustion	9 9
Ignitor - 13-inch chemical wire						
1	3/4	78.8	3	300	No ignition	9
Mixing order: hydrogen, helium, and oxygen Ignitor - 1/2-inch single manganin wire						
4 1 1	13-3/4 13-3/4 13-3/4	79.0 73.0 70.0	0.55 0.55 0.55	300 300 300	Combustion Combustion Combustion	9,10 9,10 9,10

TABLE I.- SMALL CHAMBER TEST CONDITIONS AND RESULTS - Concluded

No. of tests	Flame-path length, in.	Percent diluent	Ignition voltage, kv	Initial pressure, psia	Results	Figure
DILUENT - HYDROGEN Mixing order: oxygen, then hydrogen Ignitor - 1/2-inch single manganin wire						
1	13-3/4	70.0	1/2	750	Combustion	11(a)
2	↓	70.0	2	750	Onset of det.	11(b)
1		70.0	4	750	Detonation	11(c)
2		70.0	1/2	1000 & 1250	Combustion	
1		67.6	1/2	500	Combustion	
1		64.0	1/2	750	Combustion	
1		62.5	1	500	Combustion	
2		46.3-50.5	2 & 1	500	Detonation	
Ignitor - 1/4-inch single chemical wire						
2	13-3/4	70.3	0.09	750	Combustion	
2	↓	61.9	↓	500	Combustion	
1		54.4		500	Detonation	
1		43.9		500	Detonation	
1		34.9		500	Detonation	
1	12	49.9		500	Detonation	2(d)
1	8-1/2	55.6		500	Onset of det.	
1	3-1/4	49.9		500	Combustion	
1	3-1/4	46.9		500	Detonation	
1	3-1/4	43.9		500	Detonation	
1	1-1/2	48.4		500	Combustion	
1	1-1/2	43.9		500	Onset of det.	
1	1-1/2	37.9		500	Detonation	
Ignitor - 13-inch chemical wire						
1	3/4	70.3	3	750	Combustion	

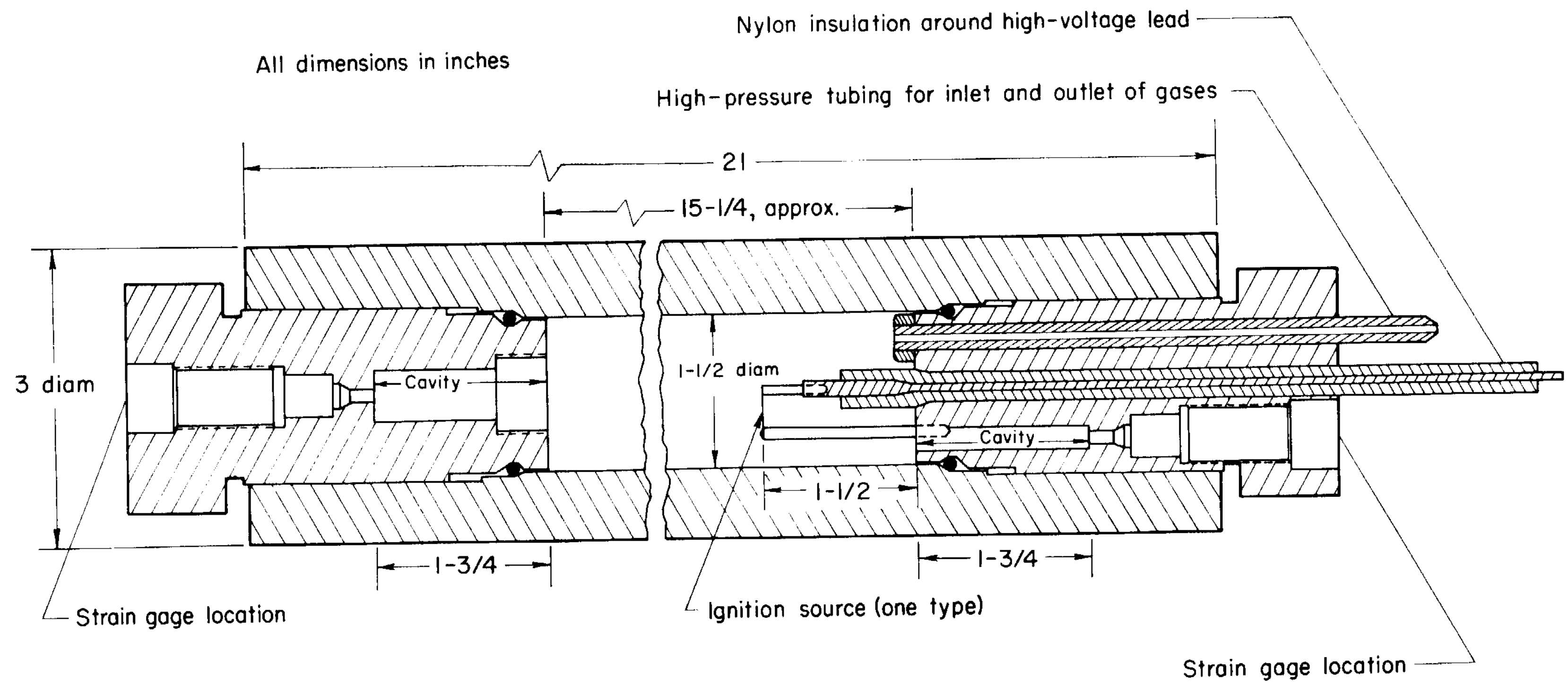
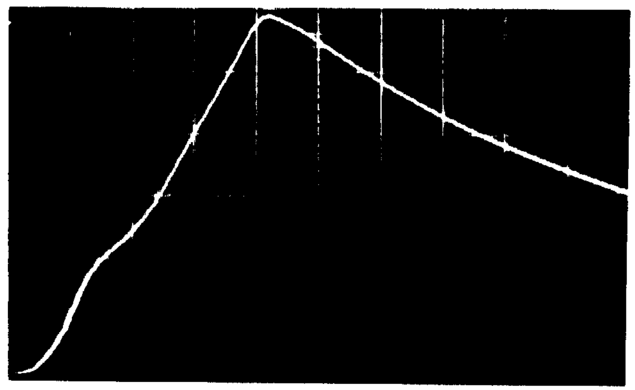
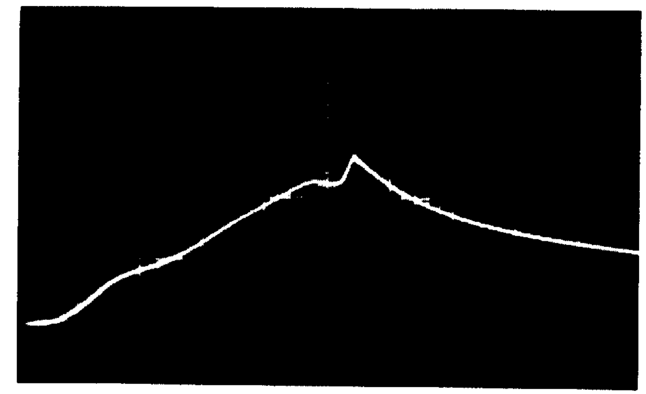


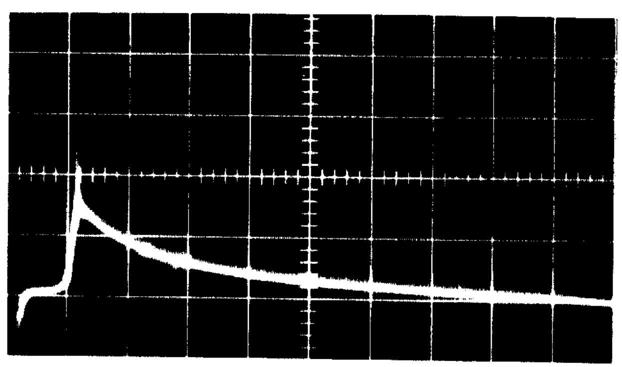
Figure 1.- Schematic sketch of small combustion chamber.



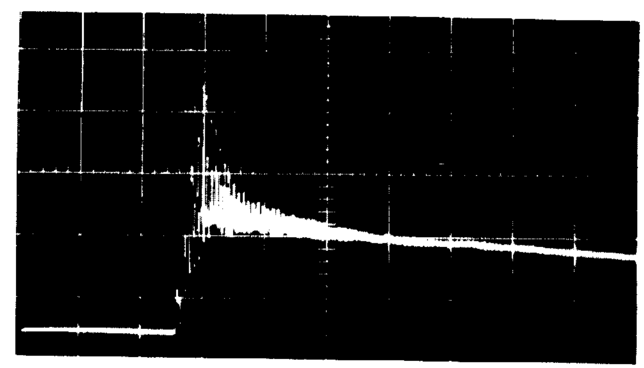
(a) Combustion.



(b) Onset of detonation.



(c) Detonation.



(d) Detonation.

Figure 2.- Pressure records from small combustion chamber.

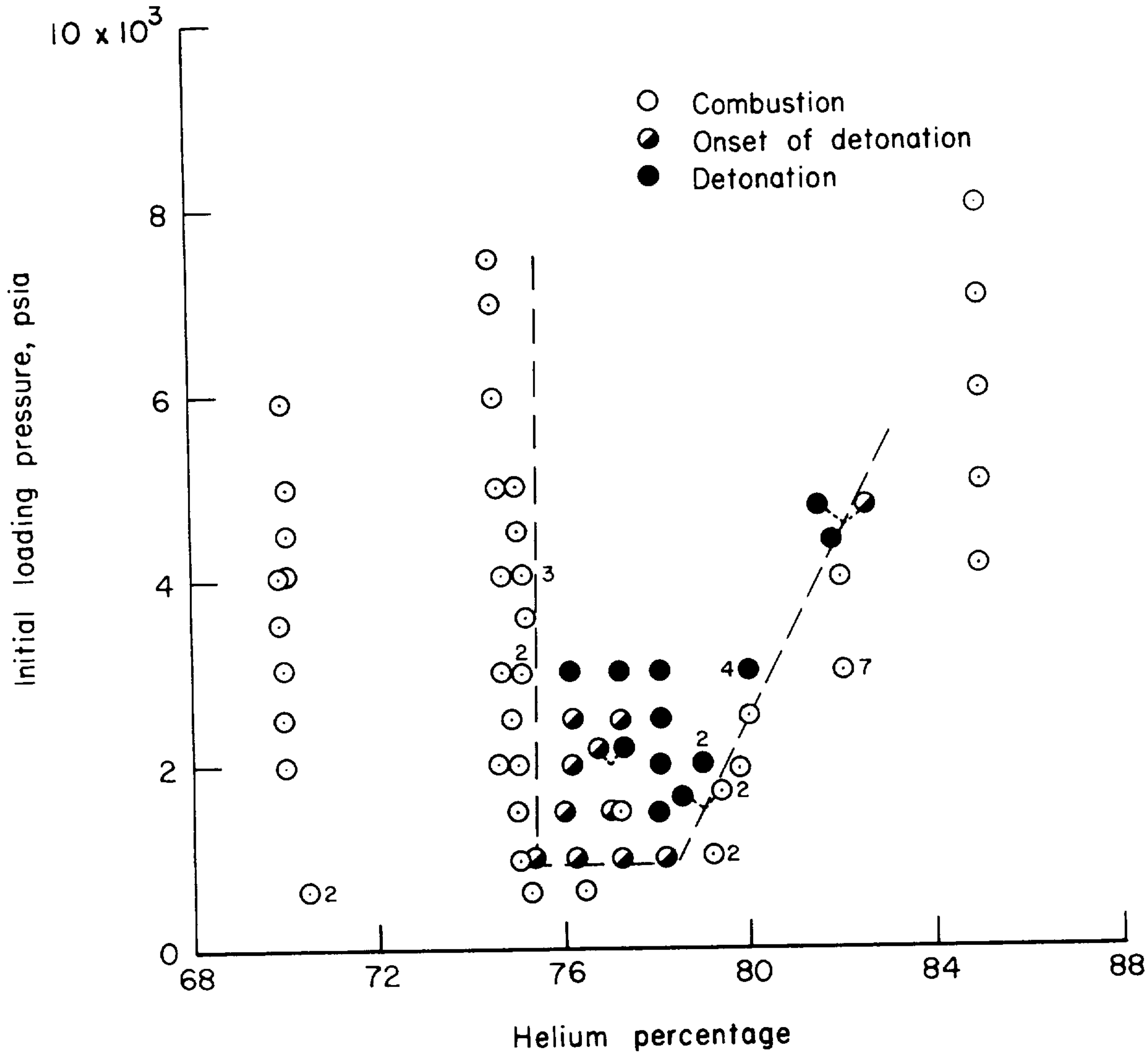


Figure 3.- Type of burning obtained at different loading pressures over a range of helium mixtures using a single 1/2-inch exploding wire with a flame-path length of 13-3/4 inches.

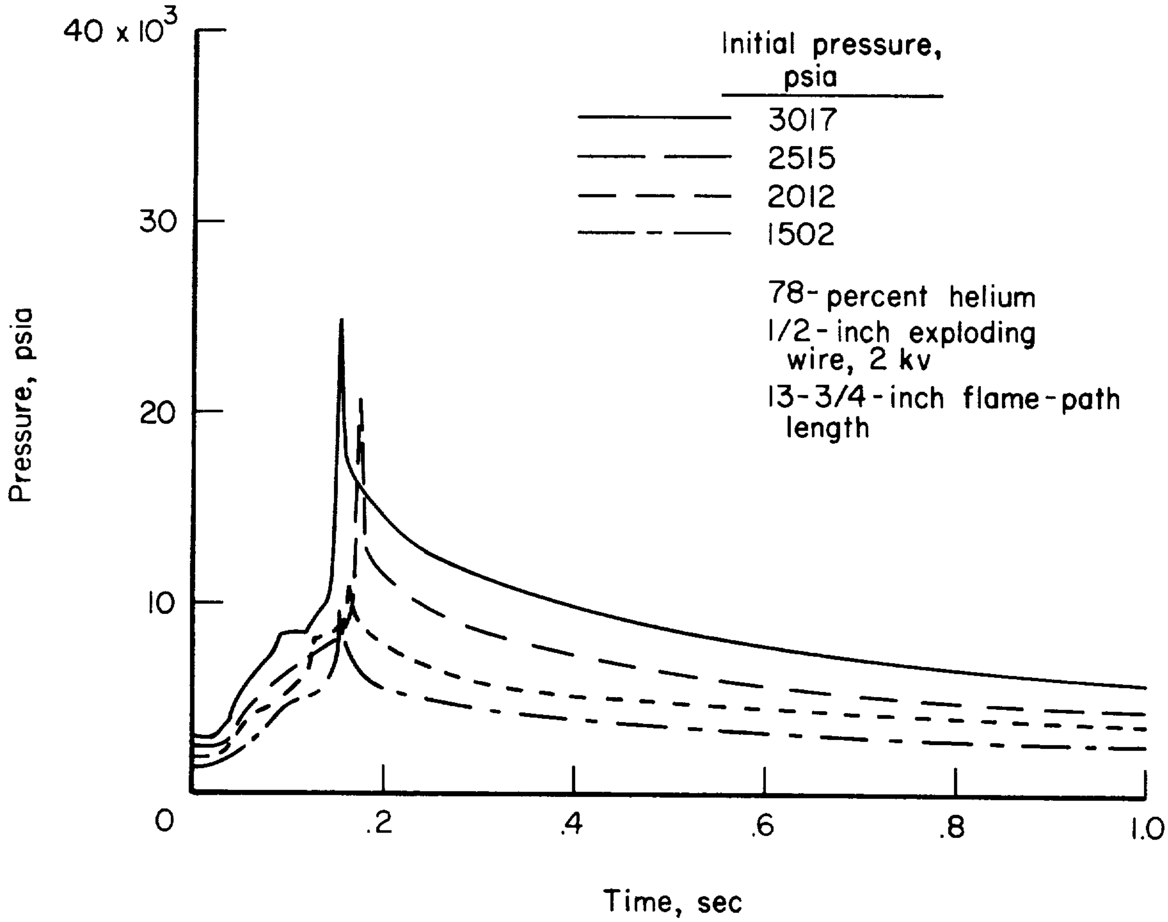


Figure 4.-Pressure versus time histories of four tests, each of which resulted in detonation.

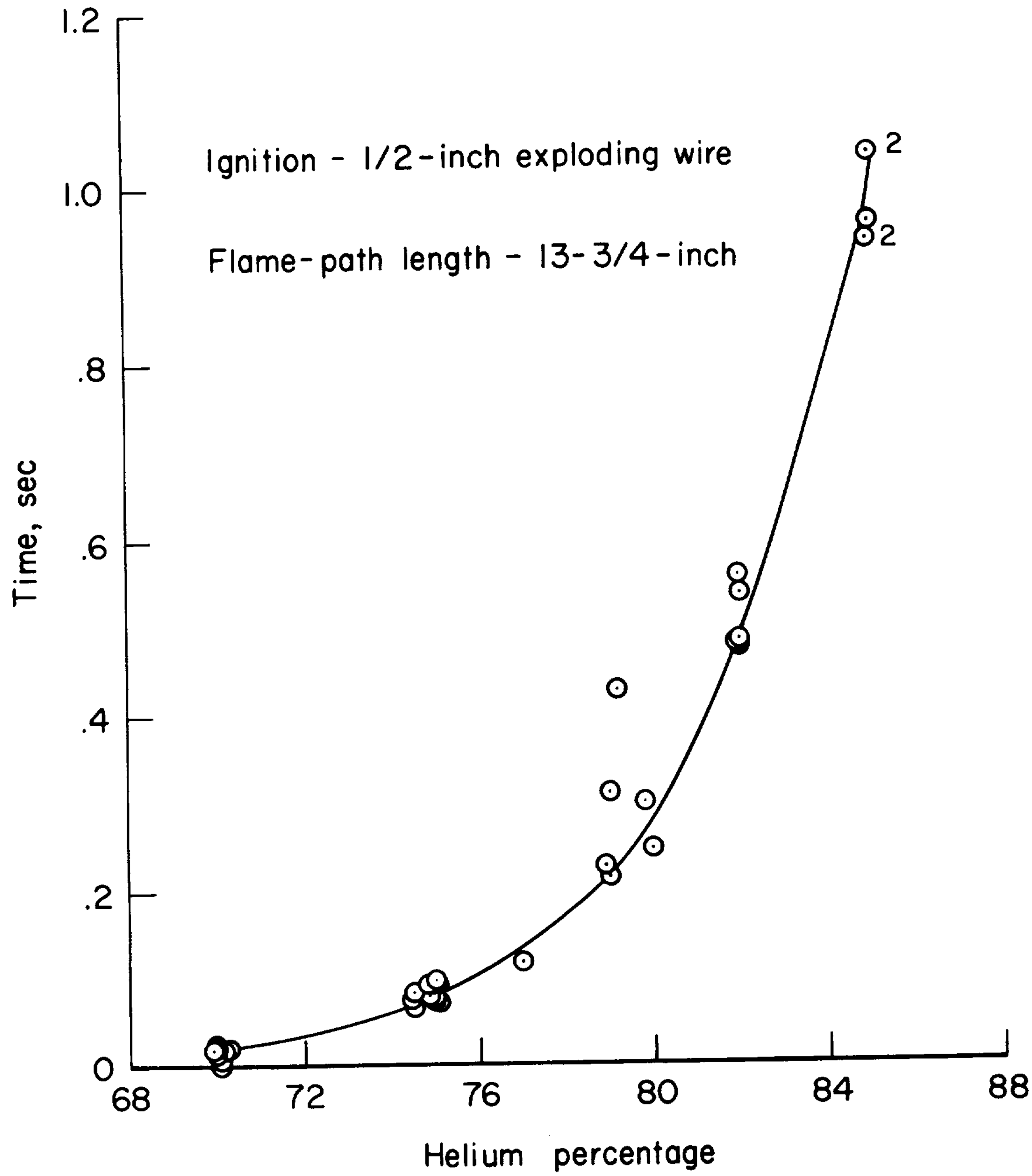


Figure 5.- The effect of helium content on burning times for initial pressures from 1,000 to 8,000 psi.

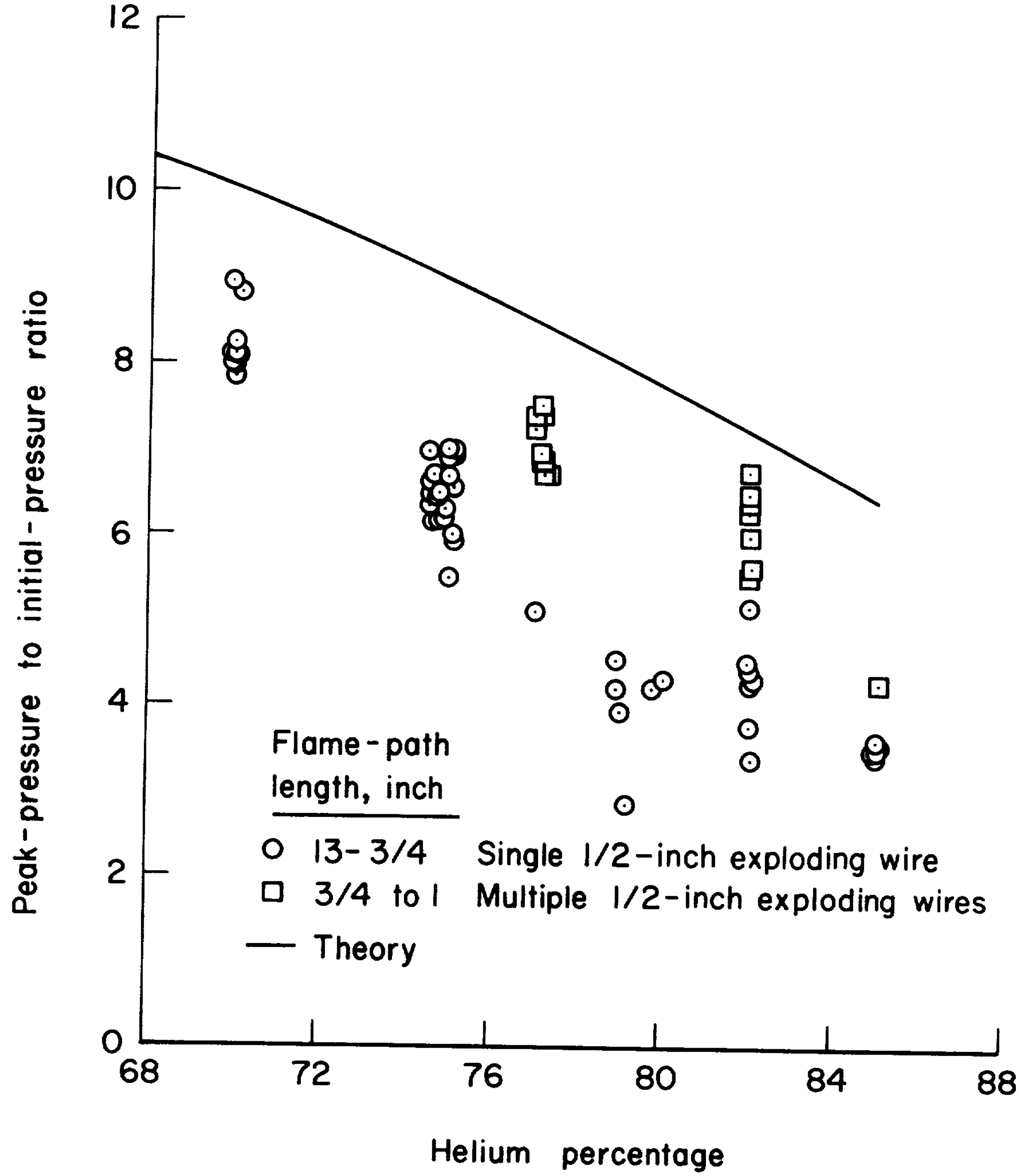


Figure 6.- Experimental pressure ratios for different helium percentage and for two flame-path lengths at initial pressures between 1,000 and 8,000 psi.

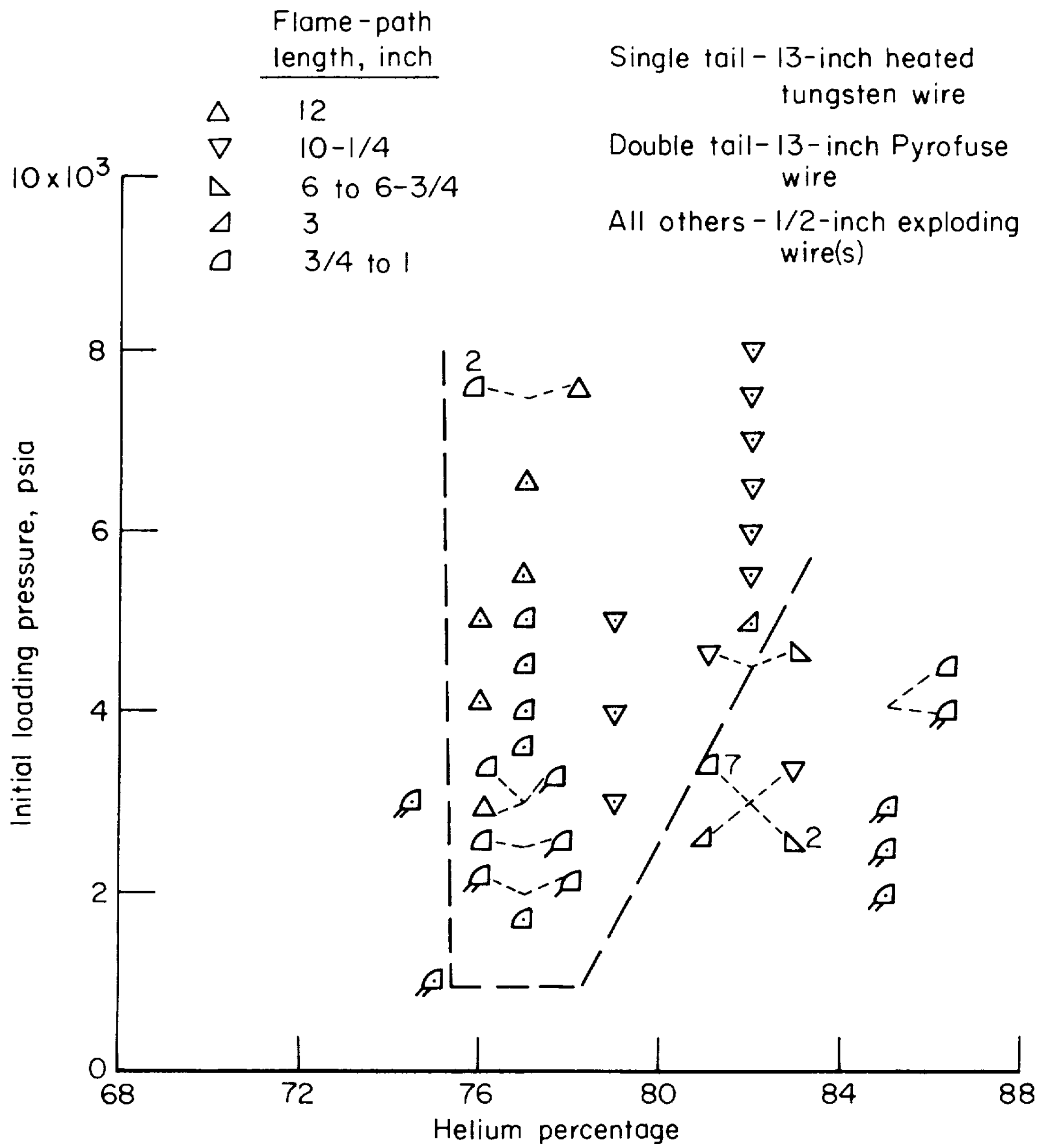


Figure 7.- Range of loading pressures and helium percentages at which combustion occurred using different flame-path lengths and ignitors.

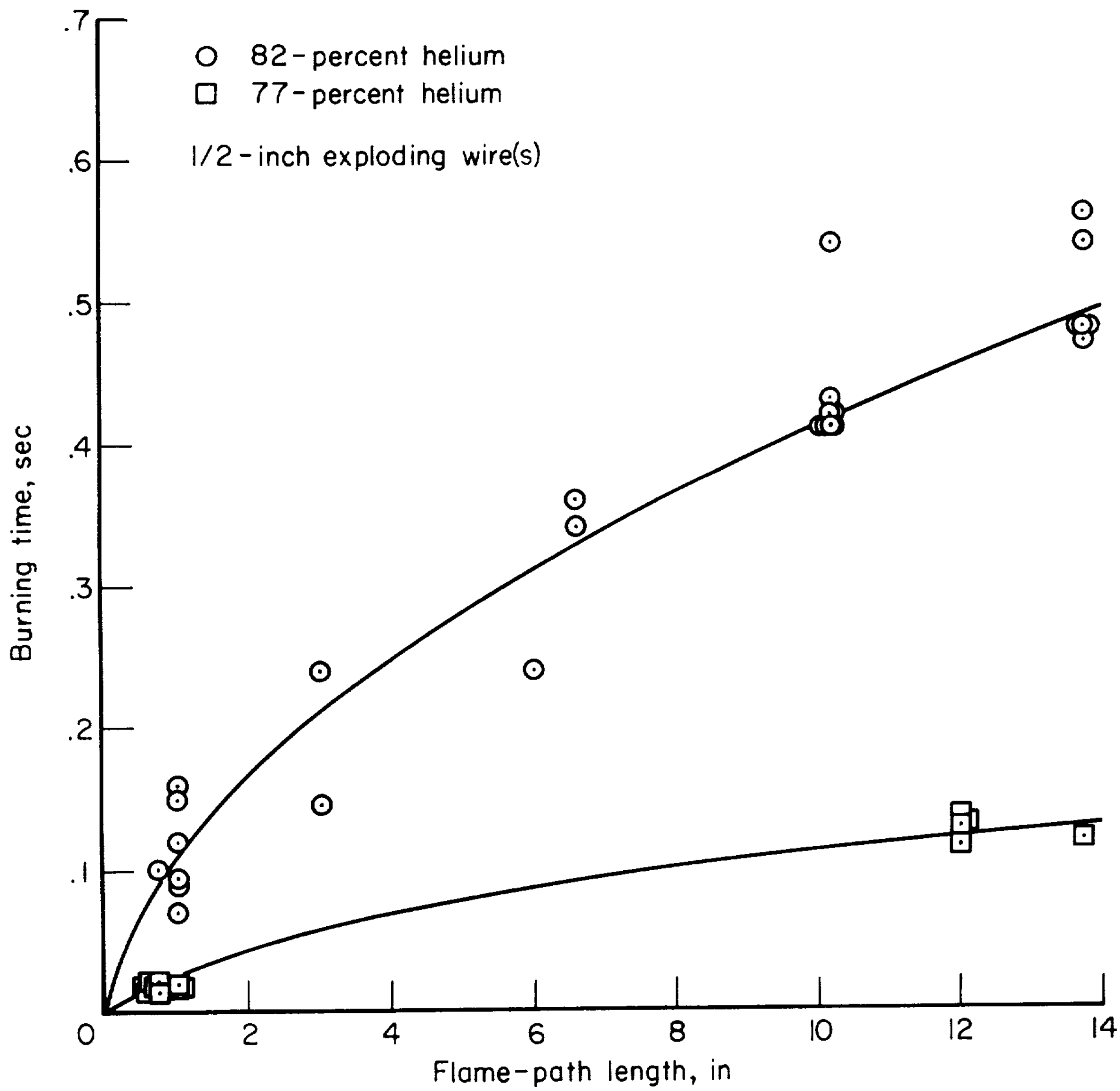


Figure 8.- The effect of flame-path length on burning time for helium mixtures of 77 and 82 percent.

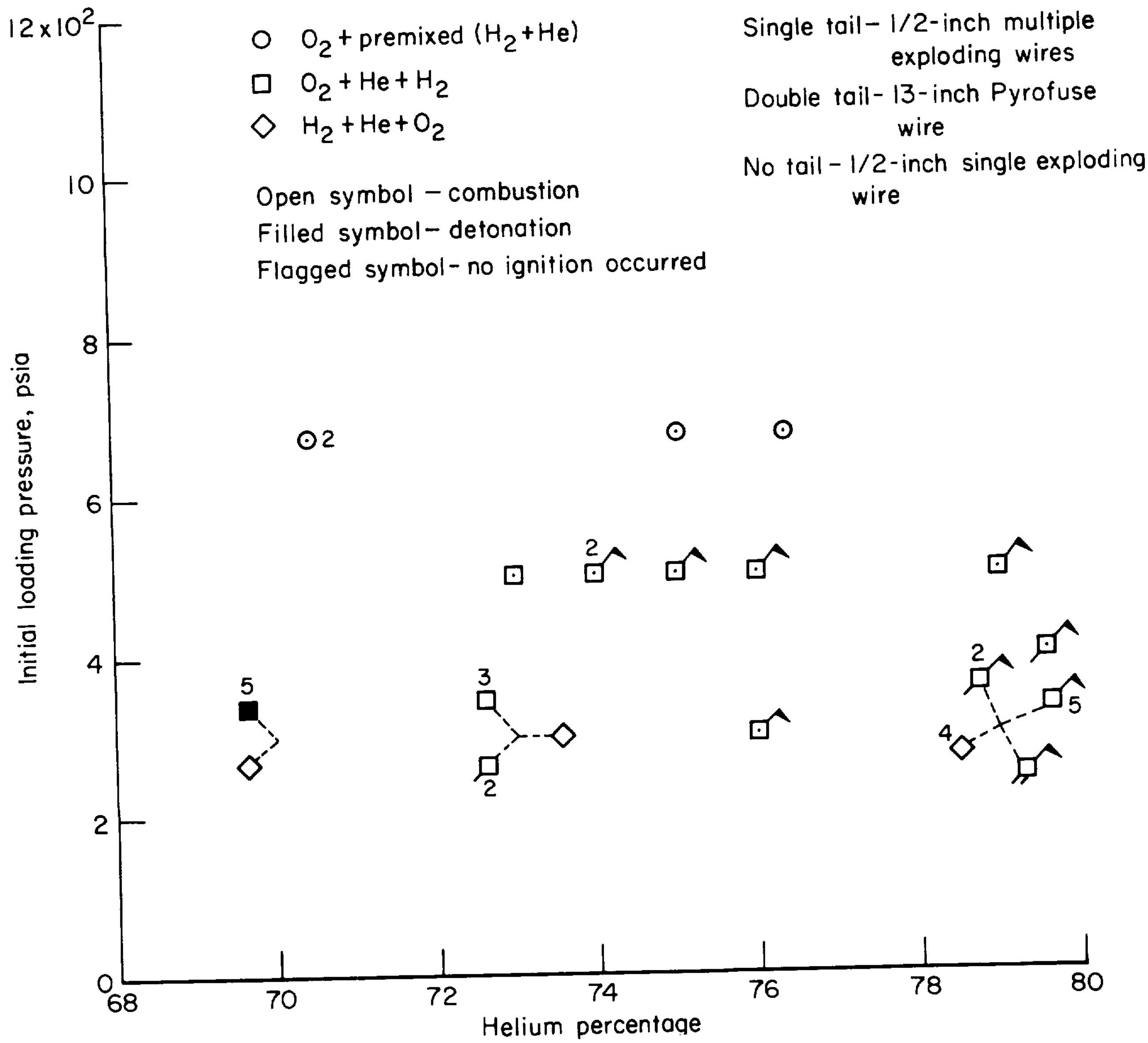


Figure 9.- Type of burning resulting from different orders of introduction of gases.

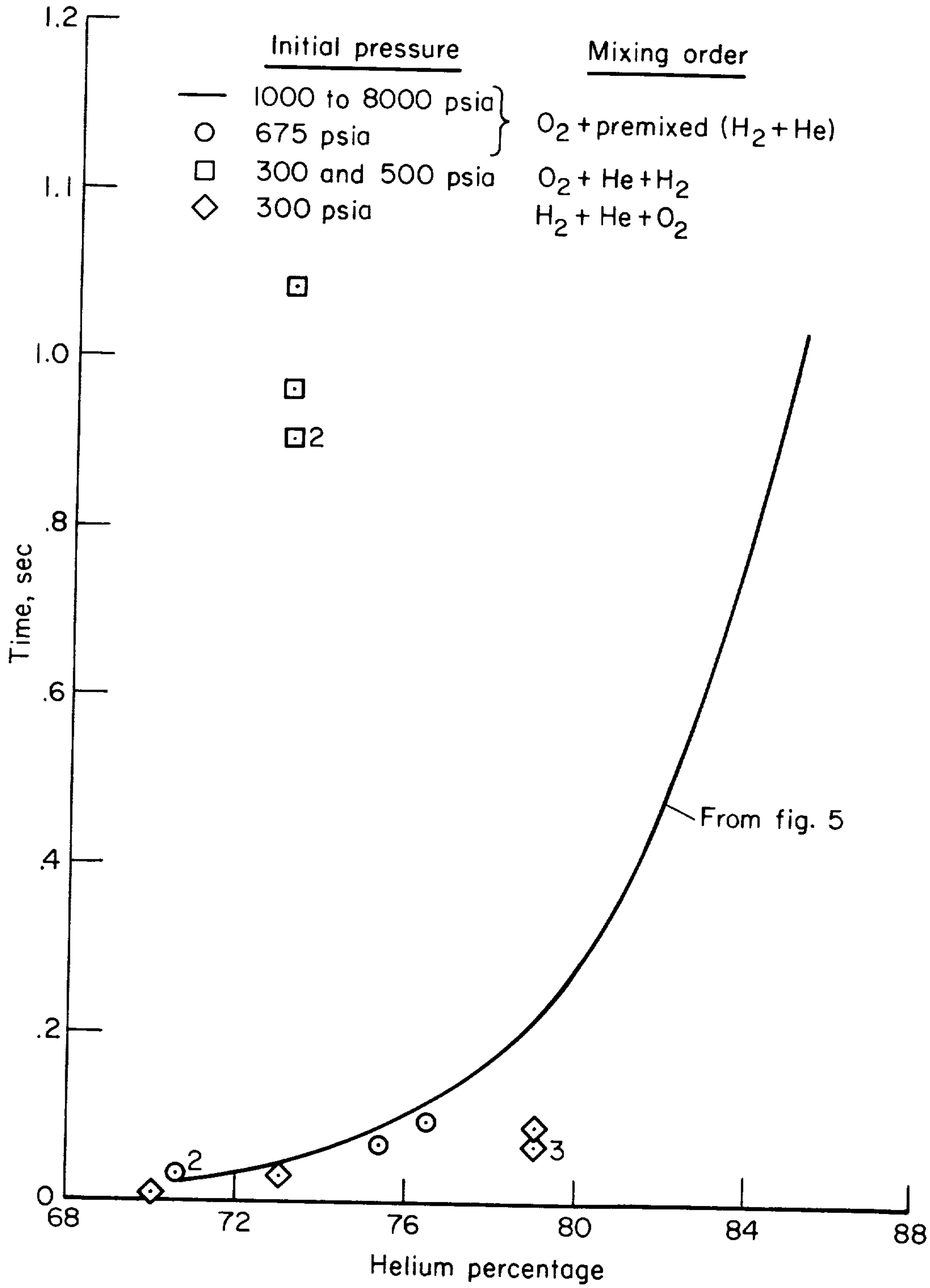
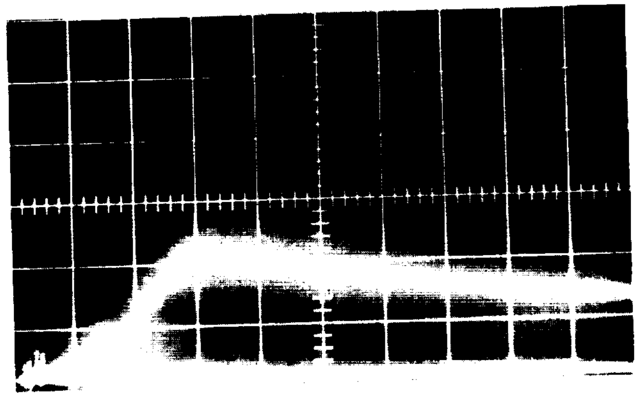
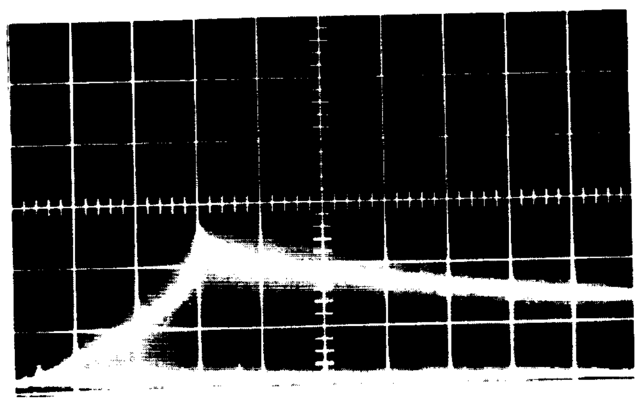


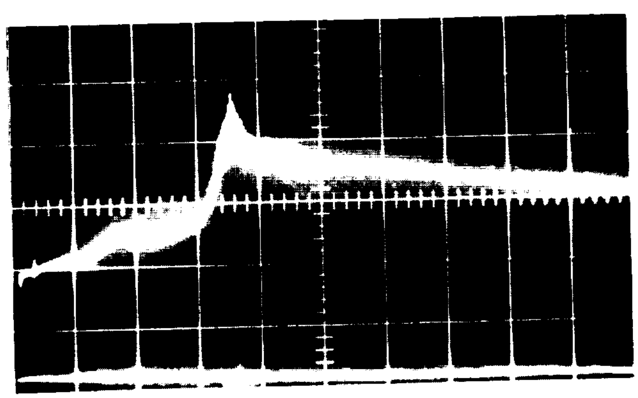
Figure 10. - The effect of mixing order on burning times as a function of helium content (1/2-inch single exploding wire).



(a) Combustion; 1/2 kv.



(b) Onset of detonation; 2 kv.



(c) Detonation; 4 kv.

Figure 11.- Effect of varying ignition voltage (capacitance of 7.5 microfarads) on type of burning in oxygen-hydrogen mixtures, 90-percent hydrogen; initial pressure, 750 psia; horizontal scale, 0.020 sec/div.; vertical scale, 1,270 psi/div.

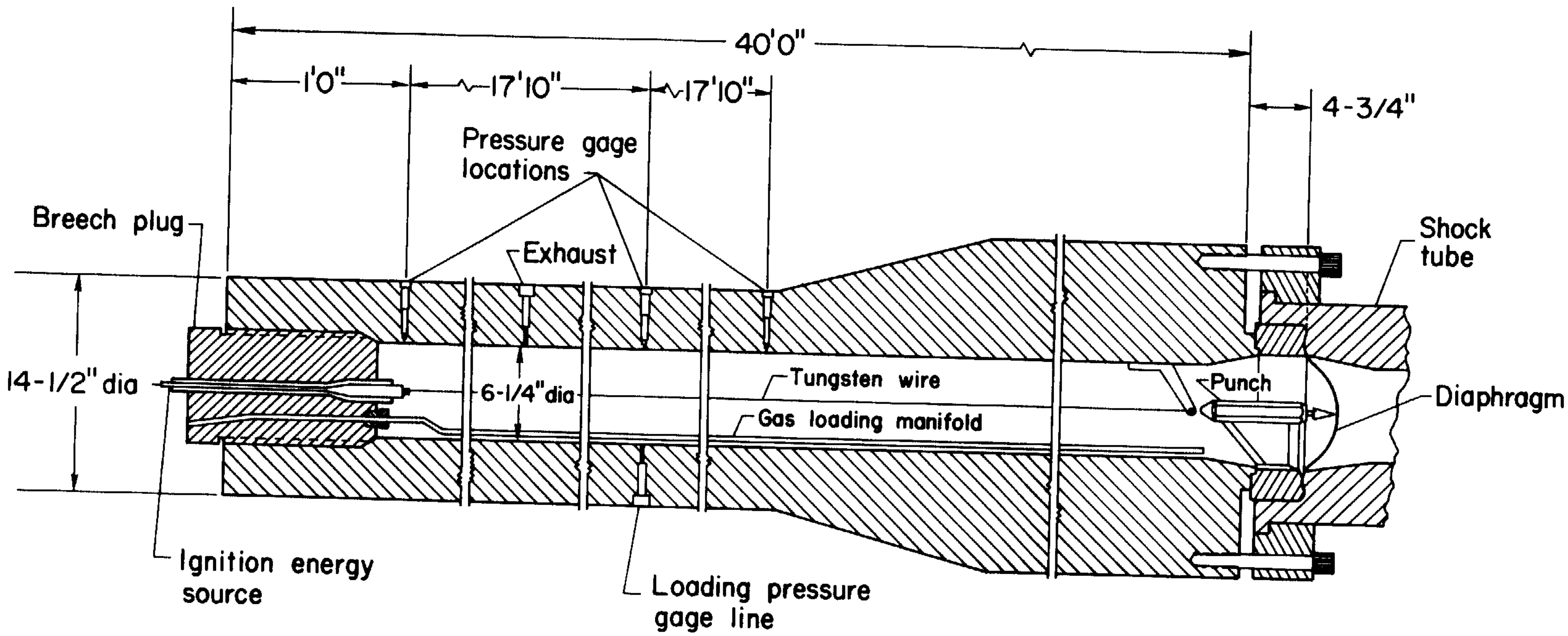
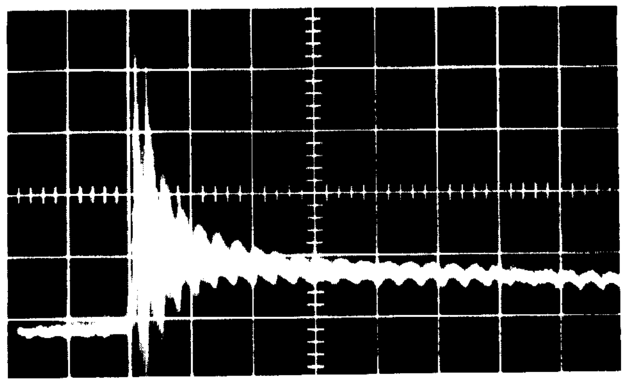
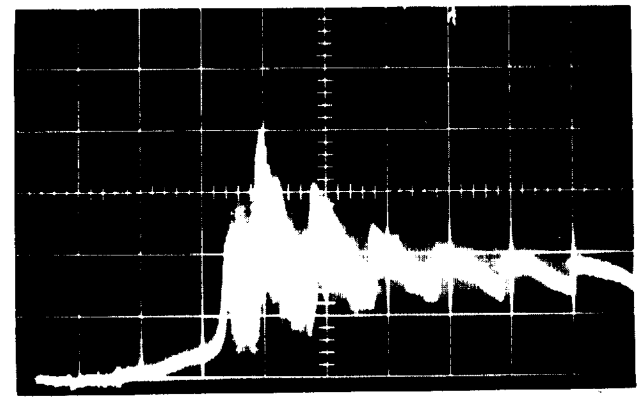


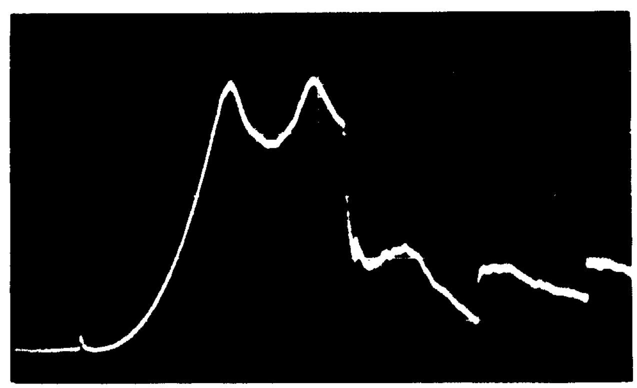
Figure 12.- Schematic sketch of large combustion chamber.



(a) Detonation with 85-percent inert mixture; initial pressure, 300 psia; horizontal scale, 0.050 sec/div.; vertical scale, 566 psi/div.

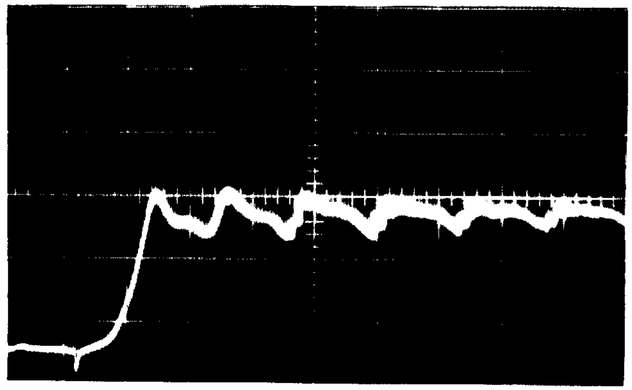


(b) Onset of detonation with 79-percent inert mixture; initial pressure, 310 psia; horizontal scale, 0.020 sec/div.; vertical scale, 566 psi/div.

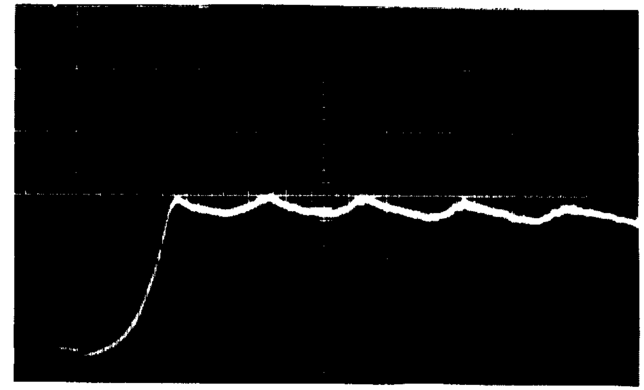


(c) Combustion with 75-percent inert mixture; initial pressure, 717 psia; horizontal scale, 0.010 sec/div.; vertical scale, 1,048 psi/div.

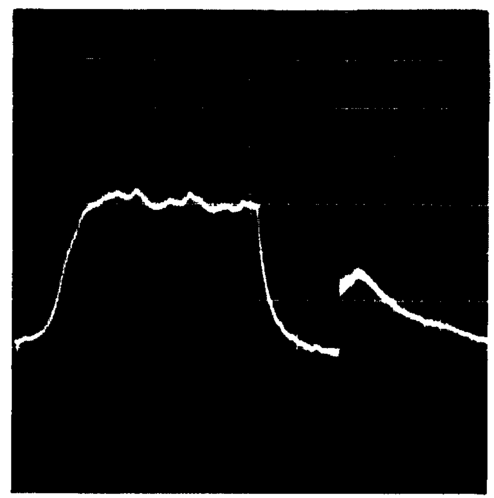
Figure 13.- Pressure records from large combustion chamber.



(d) Combustion with 75-percent inert mixture; initial pressure, 300 psia; horizontal scale, 0.010 sec/div.; vertical scale, 658 psi/div.



(e) Combustion with 75-percent inert mixture; initial pressure, 300 psia; horizontal scale, 0.010 sec/div.; vertical scale, 637 psi/div.



(f) Combustion with 75-percent inert mixture; initial pressure, 660 psia; horizontal scale, 0.010 sec/div.; vertical scale, 1,700 psi/div.

Figure 13.- Concluded.